THE HUNTERIAN LECTURES ON COLOUR-VISION AND COLOUR-BLINDNESS

F. W. EDRIDGE-GREEN

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Delivered before the Royal College of Surgeons of England on February 1st and 3rd, 1911

BY

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PREFACE

As there are many who are interested in the subject of vision and colour-blindness who are not acquainted with the structure of the eye, I will give a few details so that these persons may be able to consider the problem from the point of view of these lectures.

The eye is very similar to a photographic camera, and an actual image is formed on the back of the eye just as it is on the plate of the photographic camera or on the view-finder. The eye possesses a lens and also an iris which acts as an adjustable stop and regulates the size of the pupil. The membrane at the back of the eye upon which the image is formed is called the retina. The retina has several layers, but the sensitive layer consists of two elements called, from their shape, rods and cones. The problem therefore which has to be considered is, how is the light which forms the image on the sensitive layer of the retina transformed into visual impulses ?

Those who are interested in the subject will find further details in my book on *Colour-Blindness*

and Colour-Perception in the International Scientific Series. In that book there are three plates which show how the colour-blind see colours.

I have been annoyed to find that unauthorised persons have made lanterns professing to be mine but grossly inaccurate. The sole makers are those mentioned on page 53 in this book.

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LECTURE I

Delivered on February 1st

GENTLEMEN,—Colour-blindness is not a good name for the condition to which it is applied, and still worse is the use of the term red-blindness or green-blindness. In the majority of cases of colour-blindness there is no blindness to colours in the ordinary acceptation of the term; a green, red, or yellow light produces a very definite sensation of colour. Those who confuse red and green do so, not because they see red as green or green as red, but because both give rise to a similar sensation of colour. The word light must be used in the sense of referring to those waves which excite the organ of vision. Because two stimuli excite a sensation of light, it does not follow that they are similar. We cannot, for instance, distinguish by the eye polarised light from non-polarised light. We have to distinguish between the physical stimuli by their physical properties apart from their effect on the organ of vision. I propose to divide the subject into two parts, and in this lecture to deal with the theory and facts of colour-vision and colour-blindness, and in the second lecture with the detection of colour-blindness from a practical point of view.

I. The Theory and Facts of Colour-Vision and Colour-Blindness

The following is the theory which I have propounded in order to explain vision and colour-vision. A ray of light impinging on the retina liberates the visual purple from the rods and a photograph is formed. The rods are concerned only with the formation and distribution of the visual purple, not with the conveyance of light-impulses to the brain. The ends of the cones are stimulated through the photo-chemical decomposition of the visual purple by light (very probably through the electricity which is produced), and a visual impulse is set up which is conveyed through the optic-nerve fibres to the brain. The character of the stimulus differs according to the wave-length of the light causing it. In the impulse itself we have the physiological basis of the sensation of light, and in the quality of the impulse the physiological basis of the sensation of colour. The impulse being conveyed along the optic nerve to the brain, stimulates the visual centre, causing a sensation of light, and then passing on to the colour-perceiving centre, causes a sensation of colour. But though the impulses vary in character according to the wave-length of the light causing them, the retino-cerebral apparatus is not able to discriminate between the character of adjacent stimuli, not being sufficiently developed for the purpose. At most, seven distinct colours are seen, whilst others see in proportion to the development of

their colour-perceiving centres, only six, five, four, three, or two. This causes colour-blindness, the person seeing only two or three colours instead of the normal six, putting colours together as alike which are seen by the normal-sighted to be different. In the degree of colour-blindness just preceding total, only the colours at the extremes of the spectrum are recognised as different, the remainder of the spectrum appearing grey. Though my own opinion is that the ordinary form of congenital colour-blindness is caused by a defective development of the portion of the brain which has the function of the perception of colour, we must not exclude any portion of the retino-cerebral apparatus, defect of which would have exactly the same result. It will be noticed that the theory really consists of two parts, one concerned with the retina and the other with the whole retino-cerebral apparatus. I shall in these lectures use the word cerebral in this sense. I am not aware of a single fact which does not support this theory, and I have used it to predict facts which have subsequently been rediscovered by others and now form a part of our common knowledge.

THE VISUAL PURPLE THE ESSENTIAL FACTOR IN VISION

I will now state very briefly the evidence which supports the view that the visual purple is the essential factor in the retina which enables it to transform light into visual impulses.

1. *Anatomical.*—In the fovea of the retina only cones are to be found. Immediately external to

this each cone is surrounded by a ring of rods. The number of rings of rods round each cone increases as the periphery is reached. The outer segments of the cones are situated in a space which is filled with fluid. The external limiting membrane retains this fluid in its place. I find [1] four depressions or canals which lead into the larger depression of the external fovea. These canals appear to have smaller branches, and serve to conduct the visual purple into the part of most acute vision. The cones which are present in the fovea have very long outer segments which would present a greater surface for photo-chemical stimulation. The visual purple is only to be found in the rods and not in the cones. I determined to ascertain whether the visual purple could be seen between the cones in the fovea. I have examined under the microscope the retinas of two monkeys which had been kept previously in a dark room for forty-eight hours. The yellow spot was the reddest part of the whole retina, and the visual purple was seen to be between and not in the cones.[2]

2. *Physiological analogy with other body cells.*— It is far more probable that the rods should produce a secretion which would affect other cells rather than themselves. The liver cells do not form bile in order to stimulate themselves, and the internal secretions are produced to affect other parts of the body. I am not aware of a single instance in which a cell produces a secretion which

[1] *Journal of Physiology*, vol. xli, p. 274.

[2] *Transactions of the Opthalmological Society*, 1902, p. 300.

has the function of stimulating the cell producing it. The visual purple is regenerated in the rods by the pigment cells in connection with them.

3. *The relation between the foveal and the extra-foveal regions.*—As the fovea only contains cones, if any of the older theories of the relative functions of the rods and cones were true we should expect to find qualitative differences between the foveal and extra-foveal regions. This is not the case, but as we should expect if the visual purple were the visual substance, all the phenomena which have been attributed to the visual purple should be found in the fovea. Von Tschermak, Hering, Hess, Garten and others have found the Purkinje phenomenon, the variation in optical white equations by a state of light and dark adaptation, the colourless interval for spectral lights of increasing intensity, and the varying phases of the after-image in the fovea only gradually diminished.

4. *The varying sensibility of the fovea.*—The fovea is in some conditions the most sensitive part of the whole retina, and with other conditions the least. Helmholtz has recorded some of these facts and regarded them as quite inexplicable. We have, however, an easy explanation of the facts on the assumption that when there is visual purple in the fovea this is the most sensitive part of the whole retina, but when there is none there time must elapse before it can diffuse into the spot, and in the meantime it is insensitive to light. I have devised several experiments which show the visual purple flowing into the foveal region. The following simple experiment shows this very well.

If on awaking in the morning the eyes be directed to a dull white surface, as for instance the ceiling, the region of the yellow spot will appear as an irregular black spot, and light will appear to invade this spot from without inwards. If the eyes be now closed and covered with the hands, purple circles will form round the centre of the field of vision and gradually contracting reach the centre. When the circle reaches the centre it breaks up into a star-shaped figure and becomes much brighter. It then disappears and is followed by another contracting circle. Now it will be noticed that if one eye be opened when the circle has broken up, a brilliant rose-coloured star much brighter than any other part will be seen in the centre of the field of vision. This has the exact hue of the visual purple. If we wait until the star has disappeared before opening an eye, the macular region appears as a black spot as before. This conclusively shows that the central portion of the retina is sensitised from the peripheral portions.

5. *Chemical analogy.*—The visual purple gives a curve which is very similar to that of many other photo-chemical substances. We know that with photo-chemical substances the chemical effect is not proportional to the intensity of the light. That is, a different curve is obtained with weak light from that which is formed with light of greater intensity. It is reasonable, therefore, to suppose that the visual purple which is formed by the pigment cells under the influence of a bright light would be somewhat different in character from that which is

formed in darkness. Again, from the chemical analogy which I have just given, even if the visual purple were of the same character, we should not expect similar curves with different intensities of light. It is probable that both factors are in operation. This deduction gives an explanation of the Purkinje phenomenon, or the fact that when the eyes are adapted to darkness the point of greatest luminosity is shifted more towards the violet end of the spectrum. Some dichromics who have shortening of the red end of the spectrum have a luminosity curve which is very similar to that of a normal-sighted person with a spectrum of lesser intensity. We have only to assume in these cases either that the receiving nervous apparatus is less responsive, or that the visual purple formed at one intensity of light is similar to that formed at a lower intensity by a normal-sighted person. We also have an explanation of other conditions, such as erythropsia, or red vision, white objects appearing more or less red. If we suppose that the eye has remained in a state of light adaptation, the visual purple produced being more sensitive to the red rays, objects appear of this colour. As we should expect, erythropsia is frequently associated with hemeralopia, or difficulty in seeing in the twilight, the eyes being adapted to light and not to darkness. In green vision the eyes have probably remained in a condition of more or less adaptation to darkness, and are therefore more sensitive to the green rays.

6. *Disappearance of lights falling upon fovea.*—

If the cones are not sensitive to light, a ray of light falling upon the fovea alone and not upon the adjacent portion of the retina containing rods should produce no sensation of light, provided that there is not already any visual purple in the fovea. It has been known to astronomers for a long time that if a small star in a dark portion of the sky be steadfastly looked at, it will disappear from view, whilst other stars seen by indirect vision remain conspicuously visible. The following simple experiment shows the same thing. If a piece of black velvet about three feet square on a door have a pin put in the centre, and the source of light be behind the observer, the pin will be brightly illuminated ; and on looking at it (the observer not being too close) and keeping the eye quite still, the pin will disappear, the visual substance diffused into the fovea centralis being used up and not renewed. When viewed by indirect vision it is impossible to make it disappear in this way. When I have taken great care to have very dark surroundings and have used only one eye, I have made moderately bright lights disappear in this manner. These facts have been attributed to a defective sensibility of the fovea for feeble light. The important point, however, that the light is at first most clearly seen by the fovea and only subsequently fades, has been overlooked. If these facts were due to a defective sensibility of the fovea, the star or light would not be visible at first.

7. *Illusion of moving light.*—If a small light be looked at fixedly in a dark room, it will appear to move until it comes apparently so close that

it could be grasped. The reason of this is that the eye moves so that the light falls upon a more peripheral part of the retina. I find that the movement takes place as if some photo-chemical substance acted under the influence of gravity. For instance, when standing the light appears to travel upwards ; resting the head on one side, it appears to travel in the opposite direction. The light appears as if we were looking straight at it, and the eye, which is covered up, remains directed straight at the object. When the second eye is opened two images of the light are seen, and the image which is seen with the periphery of the first eye rapidly coalesces with that seen directly by the second eye.

8. *Purple after-image.*—A positive after-image of a purple (rose) colour can be obtained after white light or any spectral colour. It will be noticed that when there is little light during the subsequent observation the colour of an after-image inclines to blue or green, when there is more light towards purple or red.

9. *Currents seen in the field of vision not due to the circulation.*—It occurred to me that if there were canals in the retina which promoted the easy flow of the visual purple into the fovea, we ought to obtain evidence of the currents flowing along these channels entoptically. I found that this was the case, and that the currents could be seen in numerous ways.[1] If one eye be partially covered with an opaque disc whilst both eyes are directed forwards in a not too brightly illumi-

[1] *Journal of Physiology*, vol. xli, p. 269.

nated room, and special attention be paid to the covered eye, an appearance of whirling currents will be seen with this eye (see Fig. 1). These

Fig. 1.

currents appear to be directed towards the centre, and have a very similar appearance to a whirlpool which is fed by four main branches. These

again are fed by smaller branches which continually change their paths. On closing both eyes all the portion in which the whirling currents are seen appears as dull purple. These currents cannot be due to vessels, because we know that the centre of the retina corresponding to the point where the greatest movement is seen is free from vessels. The appearance is also very different from that of the movement of blood in vessels. The currents can also be seen in the light, in the dark, through yellow-green glass, and with intermittent light. The main branches form a star-shaped figure with four rays. The currents carry the visual quality, colour, and brightness from whence they come into an after-image. They also tend to move an after-image towards the centre. The currents behave as if they ran in definite channels, but could also overrun, on any further stimulus, the banks of the channels. For instance, a thin, bright line with a little more light appears as a broad band, and the central star figure will enlarge into a rhomboid, oval or disc. Movements of the eyes affect the broad currents in the outer part of the field of vision.

10. *Pressure figure.*—Pressure on the front of the eye causes the star-shaped figure to be seen, and this changes into a rhomboid with a little more pressure.

11. *Macular star.*—It occurred to me that we ought to obtain evidence of the canals in the retina in cases where the outflow from the retina is obstructed, as by tumour. I find this is the case; the star-shaped figure given by Sir Victor

Horsley in his paper on tumour of the frontal lobe is almost exactly the same as that seen subjectively.

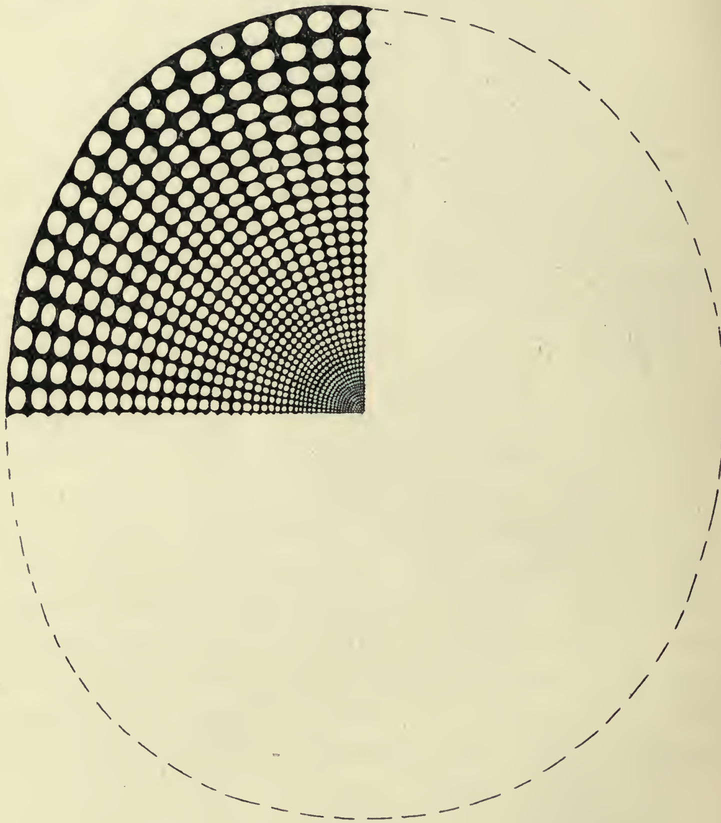


Fig. 2.

12. *Entoptic appearance of cone mosaic.*—Appearances corresponding to the cone mosaic of the retina may be seen in several ways [2] (see Fig. 2). The appearance seen corresponds to the

[1] *British Medical Journal*, 1910, p. 556.
[2] *Journal of Physiology*, vol. xli, p. 226.

cone distribution of the retina as viewed from its outer side, the portions occupied by rods appearing as dark spaces.

13. *Visual acuity.*—Visual acuity is most acute with the fovea, and diminishes from within outwards. It corresponds very fairly with the cone distribution of the retina. On the other hand, there is not one single fact which points to the rods as being light-sentient organs. This is well recognised by those best qualified to judge.[1] I could give many more facts in support of the view that the visual purple is the visual substance, and I have not yet had brought to my notice any fact which is not readily explicable on that hypothesis. There may be other photo-chemical substances in the retina, but there is not the slightest evidence that such is the case. I regard the visual purple as the sole visual substance. We could, of course, split the visual purple into innumerable simpler photo-chemical substances, each of which has its own absorption curve, having its maximum in some particular part of the spectrum. It is difficult to say at present exactly how the visual purple acts as a stimulus transformer, but this is because so many plausible hypotheses immediately occur to us. It is very probable that light acting upon the visual purple is, according to its wave-length, absorbed by particular atoms or molecules, the amplitude of their vibrations being increased. These vibrations may cause corresponding vibrations in certain discs of the outer segments of the cones, which seem

[1] *Nagel. Physiol. des Menschen*, vol. iii, p. 107.

especially constructed to take up vibrations. We know that when light falls on the retina it causes an electric current. We know how the telephone is able through electricity to convey waves of sound, and something similar may be present in the eye, the apparatus being especially constructed for vibrations of small wave-length. The current of electricity set up by light may cause the sensation of light, and the vibrations of the atoms or molecules the sensation of colour.

In all vital processes there is a condition of katabolism or chemical change in the protoplasm, and an anabolic or building-up process, in which the protoplasm is restored to its normal state. We have therefore to consider two definite processes in the visual purple—namely, a breaking down of the visual purple photo-chemically by light and its restoration by the pigment cells and rods. Under ordinary conditions of light, and during the whole of the daytime, the visual purple is continually being bleached and reformed. It is obvious, therefore, that when the eye has been kept in the dark and is then exposed to light, an observation taken immediately will not be comparable with one taken a few seconds afterwards, because in the first observation we have only to consider the katabolic change; whilst in the second observation the anabolic change has to be considered as well, as the visual purple has to be reformed for subsequent seeing. There appears to be very little evidence in ordinary circumstances of this anabolic process; for instance, if we fatigue the eye with sodium light in a dark room,

and then immediately examine a spectrum, we find that though all the yellow has disappeared there is no increase in the blue ; in fact, the blue seems rather diminished than otherwise. Again, there is not the slightest diminution in either the red or green, showing conclusively that yellow cannot be a compound sensation made up by a combination of red and green. We must therefore explain in another way the apparent trichromatism of normal colour-vision, which is so well known to every photographer, especially those who are concerned with colour photography. If my theory of the evolution of the colour-sense be the correct one, and we have cases of colour-blindness corresponding to every degree of the evolutionary process, we have an explanation of the facts. In past ages all saw the rainbow made up of only three colours—red, green, and violet. When a new colour (yellow) appeared between the red and green, it is obvious that a mixture of red and green would give rise, not to red-green, but to the colour which had replaced it—namely, yellow. The retina, therefore, corresponds to a layer of photo-chemical liquid in which there are innumerable wires each connected with a galvanometer. When light falls upon a portion of this fluid the needle of the galvanometer corresponding to the nearest wire is deflected. The wires correspond to the separate fibres of the optic nerve, and the galvanometers to the visual centres of the brain.

Cases of colour-blindness may be divided into two classes, which are quite separate and distinct

from each other, though both may be present in the same person. In the first class there is light as well as colour loss. In the second class the perception of light is the same as the normal-sighted, but there is a defect in the perception of colour. In the first class certain rays are either not perceived at all or very imperfectly. Both these classes are represented by analogous conditions in the perception of sounds. The first class of the colour-blind is represented by those who are unable to hear very high or very low notes. The second class of the colour-blind is represented by those who possess what is commonly called a defective musical ear. Colour-blind individuals belonging to this class can be arranged in a series. At one end of this series are the normal-sighted, and at the other end the totally colour-blind. The colours appear at the points of greatest difference, and I have classified the colour-blind in accordance with the number of colours which they see in the spectrum. The normal-sighted may be designated hexachromic; those who see five colours, pentachromic; those who see four, tetrachromic; those who see three, trichromic; those who see two, dichromic; and those who see none, totally colour-blind. There are many degrees included in the dichromic class. There may or may not be a neutral band, and this is widest in those cases approaching most nearly to total colour-blindness. I have recorded a case of a patient who was colour-blind with one eye.[1]

[1] "Colour Blindness and Colour Perception," *International Scientific Series*, p. 196.

It is an interesting fact that for form vision the colour-blind eye was much the better of the two, and he could recognise fine lines in the spectrum with this eye which were not visible to the other. He saw the two ends of the spectrum tinged with colour and the remainder grey. It will be noticed that his colour sensations were limited to the extreme red and the extreme violet—namely, those colours which present the greatest physical contrast to each other. Neither the red nor the violet appeared of the nature of a primary colour, but gave the impression that they were largely diluted with grey. A theory of colour-vision must account for a case of this kind, and also for the other varieties and degrees of colour-blindness. The trichromic are a very important class, and any theory must account for the fact that they see yellow as red-green, and blue as violet-green. As we should theoretically expect, when there is shortening of the spectrum the centres of the colours are moved towards the unshortened side.

I will now show on the screen some representations of pictures painted by colour-blind persons. The upper picture is the copy, and the one below is the one which has been painted by the colour-blind artist. He has been given a selection of colours on plates, and from them has selected the one which he thought appropriate in each case. It will be noticed that the mistakes made are characteristic of the colour-perception of the person painting them. Whenever I show these pictures, I am asked why it is that these characteristic mistakes should be made, and that

the true colour of the object is not used instead? This undoubtedly would be the case if the artist were allowed to match the colours by directly comparing them. But he is not able to do this; he looks at the copy and decides upon the colour of an object, and then looks for the colour with which to paint it.

A man rarely uses a hue which he does not see as a definite colour, and therefore it has been quite possible for me to pick out those who are more or less colour-blind in the exhibitors of the picture gallery. For instance, if a trichromic have to paint a yellow object he will decide, after looking at it, whether it be a red or green in his estimation, and represent it accordingly. He will be greatly influenced by the nature of colours in its immediate proximity, because simultaneous contrast is increased in the colour-blind. Thus he will certainly represent a yellow which is adjacent to a red as green, and a yellow which is adjacent to a green as red.

THE EVOLUTION OF THE COLOUR-SENSE

There can be no doubt that an evolution of the colour-sense has taken place: the only point is how and when did this occur. It is obvious that in those low forms of animal life in which the most rudimentary sense of sight exists there can be no sense of colour. The animal which can only perceive light and shade can only discriminate in a rough way between varying intensities of the stimulus. It is obvious, therefore, that the sense of light must have been developed first and then the

sense of colour. The sense of sight must have been first developed for those waves which produce their maximum effect upon the sensitive protoplasm. The next process of development would be for the protoplasm to become sensitive to the waves above and below those which produced the primary stimulus. In the physical stimulus which produces the sensation of light there are two factors to be considered, the length of the wave and its amplitude: the greater the amplitude within certain limits the greater the intensity of the sensation. The wave-length of the physical stimulus is the physical basis of the sensation of colour. How did the sensations of colour first arise? Let us suppose that the physiological effect of the physical stimulus differed according to the wave-length of the physical stimulus.

Let us consider that the eye has reached a stage in which it has become sensitive to a fair range of the spectral rays; that is to say, evolution has proceeded to the extent of making the protoplasm sensitive to rays of light considerably above and below those which first caused a sensation of light. We now have an eye which is sensitive to the greater part of the rays which form the visible spectrum. It is, however, an eye which is devoid of the sense of colour; no matter from what part of the spectrum the rays be taken the only difference which will be appreciated will be one of intensity. I however mentioned that in the physical stimulus there were two variables, wave-length and amplitude of the wave. Let us now suppose that a fresh power of discrimination was

added to the eye and that it became able to discriminate between different wave-lengths of light. What would be the most probable commencement of development of the sense of colour? Undoubtedly to my mind the differentiation of physical stimuli which were physically most different. That is to say, the eye would first discriminate between the rays which are physically most different in the visible spectrum, the red and the violet, that is presuming the eye had become sensitive to this range. It is probable that it had not, and there has been a steady evolution as to the extent of the spectrum perceived as well as to colour. We have examples of this in those cases of defective light-perception in which there is shortening of the red or violet end of the spectrum.

Let us now work out the evolution of the colour-sense on the assumption that the rays which are physically most different, namely, red and violet, were those which were first differentiated. We know that the various rays differ in their effects on various substances; the red rays are more powerful in their heating effects, whilst the violet rays are more active actinally, as is well known by the readiness with which they act upon a photographic plate, which is scarcely affected by red light. We should now have an individual who would see the spectrum nearly all a uniform grey of different degrees of luminosity, but with a tinge of red at one end and a tinge of violet at the other. There is a great deal of evidence to show that this is how the colour-sense was first developed. For instance,

in the degree of colour-blindness just preceding total the spectrum is seen in this way. I have also examined a woman who became totally colour-blind, apparently through disease of the ear. I examined her when she had recovered a certain amount of colour sensation ; her sensations were confined to the extreme red and violet. As the colour sense developed it was not necessary that the rays should differ so much in refrangibility before a difference was seen, and so the red and violet gradually invaded the grey or neutral band, until at a certain point they met in the centre of the spectrum. Such cases are called dichromics.

The next stage of evolution of the colour-sense is when the colour-perceiving centre is sufficiently developed to distinguish three main colours in the spectrum. The third colour, green, appears in the centre of the spectrum, that is, at the third point of the greatest physiological difference. In accordance with the prediction of the theory, I found a considerable number of persons who saw the spectrum in this way, about 1·5 per cent of men. The trichromic see three main colours in the spectrum—red, green, and violet. They usually describe the spectrum as consisting of red, red-green, green, green-violet, and violet. They do not see yellow and blue as distinct colours, and are therefore in continual difficulty over them. There are very few of the tests in general use which can detect them, especially if names be not used. They will usually pass a matching test with ease. An examination with the spectrum shows that their colour-perception is less than the normal in

every part, though the curve has the same general shape. The three trichromics described in my recent paper [1] on "The Relation of Light-Perception to Colour-Perception" each saw ten consecutive monochromatic patches in the spectrum instead of the eighteen or nineteen seen by those who see six colours in the spectrum. It is easy to show that the trichromic are dangerously colour-blind. They will mark out with my colour-perception spectrometer a patch containing greenish yellow, yellow, and orange-yellow, and declare that it is absolutely monochromatic. When tested with coloured lights they find great difficulty with yellow and blue. Yellow is continually called red or green.

There are several other degrees of colour perception, and it may be well to say a word or two about them, though I class all above the trichromic with the normal-sighted for practical purposes, as they are not dangerously colour-blind, and can always, in ordinary circumstances, distinguish signal lights correctly. In the next stage of evolution four colours are seen in the spectrum, and the fourth colour appears at the fourth point of greatest physiological difference, namely, at the orange-yellow of the hexachromic or six-colour people. These persons I have designated "tetrachromic," because they see four distinct colours in the spectrum, that is, red, yellow, green, and violet. They do not see blue as a definite colour, and are continually classing blues with greens; they usually prefer to call blue, purplish green.

[1] *Proceedings of the Royal Society*, vol. B 82, 1910, p. 458.

In the next stage of evolution there appeared those who see five colours in the spectrum—red, yellow, green, blue, and violet, blue being now recognised as a definite colour. These are the pentachromic group. These people pass all the tests in general use with ease. They, however, have a definitely diminished colour-perception compared with the normal, or those who see six colours in the spectrum. They mark out in the spectrum only fifteen monochromatic patches instead of eighteen. They cannot see orange as a definite colour; for instance, they can never tell whether a strontium light, which is red, or a calcium light, which is orange, is being shown them.

In the next stage of evolution orange is recognised as a definite colour, and thus we get the hexachromic or normal group, and, as we should theoretically expect, the yellow of the pentachromic is now split up into two colours—orange and yellow. The last stage of evolution which we appear to have reached are those who see seven colours in the spectrum, and the additional one is called indigo. These constitute the heptachromic group, and this seventh colour appears at the exact point at which it should appear, according to my theory, namely, between the blue and violet. Persons belonging to this class have a marvellous colour-perception and memory for colours. They will indicate a certain shade of colour in the spectrum, and then next day will be able to put the pointer at precisely the same point, a feat which is quite impossible to the ordinary

normal-sighted person. They see a greater number of monochromatic patches in the spectrum than the hexachromic, but the curve has the same form. The marking out of the heptachromic does not appear correct to those who see six colours; for instance, the blue appears to invade the green, and the indigo does not appear a definite colour at all. If, however, we bisect the blue of the seven-colour man, and then bisect his indigo, on joining the centres we get the blue of the six-colour man, showing most definitely that the blue has been split up into two fresh colours. It will be noticed that there is room for much further evolution, and we could go on splitting up the spectrum indefinitely if only we had the power to distinguish these finer differences, but as a matter of fact I have never met with a normal-eyed man who could see more than twenty-nine monochromatic patches in the spectrum, and there are really millions, though by monochromatic patches I do not mean twenty-nine separate colours. Not only are all the details of the process of the evolution of the colour-sense supported by all the facts that we can obtain from literature and museums, but the theory accounts for facts which were previously inexplicable. The distinction between light-sensation and colour-sensation is explained, and all facts of colour-mixing, complementary colours, and simultaneous contrast. We can understand how, as in many cases which have been recorded, a man may lose his colour-perception and still have an unaltered sense of luminosity and visual acuity.

The explanation of complementary colours is a fundamental part of the theory. It is obvious that the two colours of the dichromic are only recognised as different because they are seen in contrast to each other, and that when they are mixed they neutralise each other. It is the same with the other colour-sensations, when they are developed they replace the colours occupying their positions. Therefore green which replaces the grey of the dichromic should be, and is, complementary to the other two colour-sensations, red and violet combined. In the same way when the yellow sensation replaces the red-green of the trichromic it should be possible to compound it of both. Also, when the green sensation is in a feeble state of development it will not have the value that it has at a subsequent stage, and, therefore, yellow will be a much redder colour to those persons than the normal, and in a colour match of red and green forming yellow, more green will be required.

Simultaneous contrast is also explained. When two colours are contrasted each appears to be a colour higher or lower, as the case may be, in the spectrum scale ; that is to say, the close comparison exaggerates the difference. As the colour-blind have fewer colours, simultaneous contrast should be greater with them, and this I have found to be the case.

There may be some relation between the monochromatic patches and the discs in the outer segments of the cones. These are about sixteen in number in the guinea-pig. As in photography,

the intensity of the light is a very important factor in vision. With colours of moderate intensity, the periphery of the retina is found to be colour-blind, but this apparent colour-blindness disappears when more intense lights are used. A person may have shortening of the spectrum with light of moderate intensity, but when the light is increased be able to recognise the spectrum to its normal limit. The change in steepness of gradation, according to the intensity of the light, is well known to photographers. The Purkinje effect, a change in maximum sensitiveness of the eye according to the intensity of the light, is, in my opinion, a photo-chemical effect. I find that the Purkinje effect is found for small portions of the retina if a black object has been situated in the corresponding part of the field of vision. The yellow pigment which is found in the yellow spot probably acts like the yellow screen in photography, which, by absorbing the blue and violet rays of the atmosphere, renders visible that which would otherwise be invisible. This is further borne out by the fact that hunters in India are able to hunt later in the day than usual by using spectacles glazed with golden yellow glass.

THE FACTS OF COLOUR-BLINDNESS

When we consider the path along which a visual impulse has to pass, and that each cell has probably some special function in connection with that impulse, it is not surprising that we meet with a large number of different defects of colour-perception and light-perception. Defects

of light-perception are quite distinct from defects of colour-perception.

1. *Defects of light-perception.*—The person having the defect is placed in a similar position to a normal-sighted person with those particular rays removed or reduced to the same intensity. Defects of light-perception may be caused by absorption or by some defect in the visual purple or cerebro-retinal apparatus. The chief defect of light-perception which is found is shortening of the red or the violet end of the spectrum. Let us consider the influence of a shortened spectrum upon colour-vision. The first evident fact is that bodies reflecting only light, the rays of which occupy the missing portion of the spectrum, appear black.

Nearly all colours are compound; that is to say, the coloured body reflects other rays than those of the colour seen. Thus a blue-green glass may transmit the green, blue, and violet rays of the spectrum. Let us suppose that we have a substance reflecting the green, blue, and three-quarters of the violet, the colour of the body to a normal person being green. Then if we had another substance which reflected the whole of the violet, it would appear blue. But with a person who could not perceive the terminal fourth of the violet the colour would look exactly the same as the green one, and as he could not distinguish between the two he would be in continual difficulty with blues and greens. All coloured objects reflecting rays occupying the missing portion appear darker than they do to

the normal-sighted, and are always matched with darker colours belonging to a point more internal. Thus a dichromic with a shortened red end of the spectrum matches a red with a darker green.

It will be noticed that a shortened spectrum, especially if one end only be affected, may interfere very little with the general appreciation of shade. If, for instance, we take a case in which the red end of the spectrum is shortened, so that only three-quarters of the red of the normal-sighted is seen, then all bodies which equally reflect or transmit these rays can be correctly compared, because a similar portion of light has been removed from each. It is only when one colour reflects or transmits the rays occupying the shortened portion, and the other does not, that there is any definite interference with the appreciation of shade. Again, if neither colour reflects or transmits rays occupying the shortened portion of the spectrum, there will obviously be no interference with the appreciation of shade.

A very common mistake due to shortening of the red end of the spectrum is the confusion of pink and blue. If a person with considerable shortening of the red end of the spectrum is shown a pink which is made up of a mixture of red and violet, the red consisting of rays occupying the missing portion of the spectrum, only the violet is visible to him, and so the pink appears a violet without a trace of red. This pink is therefore matched with a violet or blue very much darker than itself.

Mistakes which are due to shortening of the spectrum may be remedied if we subtract the rays occupying the missing portion from the colour of confusion. For instance, if we take a blue and a pink which have been put together as identical by a person with a shortened red end of the spectrum, and look at them through a glass which is opaque to the red, but transparent to the remaining rays of the spectrum, both will appear alike in hue and shade. A person with considerable shortening of the red end of the spectrum will look at a red light (which is so dazzlingly bright to a normal-sighted person as to make his eyes ache after looking at it closely for a few seconds), at a distance of a few inches, and remark that there is nothing visible, and that the whole is absolutely black. It is obvious that the light must consist only of rays occupying the missing portion of the spectrum. The same remarks which I have made for a shortened spectrum apply to cases in which there is defect of light-perception through absorption or any other cause. The person having the defect is placed in a similar position to a normal-sighted person with those particular rays removed or reduced to the same intensity.

Another effect of shortening of the spectrum when it is sufficient to interfere with the difference-perception which appears to be inherent in the central nervous system, is that the colours appear to be moved in the direction of the unshortened portion. For instance, we find the neutral point of the dichromic, with shortening of the red end

of the spectrum, in most cases further towards the violet end of the spectrum in comparison with a case in which the spectrum is of normal length. In the same way a trichromic with a shortened red end of the spectrum has the junction of the red and green nearer the violet end than in a case where there is no shortening.

The point that I specially wish to emphasise is that, though every case in which there is defective light-perception can be explained by a defective sensibility to light of certain wave-length, not a single case of the very large number of persons that I have examined can be explained on the older theories; that is, the defect of light-perception cannot be explained on the assumption that there is a defect in a light-perceiving substance which is sensitive to rays of light from a considerable range of the spectrum. A large number of cases in which there is shortening of the red end of the spectrum escape detection when only the green test is used, as is usual according to Holmgren's instructions.

2. *Defects of colour-perception.*—The colour-blind have a diminished hue-perception and see a less number of colours than the normal. All the symptoms of colour-blindness are such as we should expect from want of development of the retino-cerebral apparatus for the perception for colour. This is evident even in the slighter cases which show a diminished colour-perception compared with the normal. We find that the colour-blind are much more dependent on the luminosity of the colour than the normal-sighted; they re-

quire a stronger stimulus; they fatigue more easily with colours than the normal-sighted; they have a more marked simultaneous contrast; the visual angle subtended by the coloured object requires to be larger, and they have a very bad memory for colours. The diminution of colour-perception with a diminished visual angle evidently depends upon several causes. It is very marked when there is diminished light-perception for those rays which are imperfectly seen. It is also dependent upon certain retinal conditions, as in scotoma and allied conditions. There are colour-blind persons, however, who are able to recognise colours under as small a visual angle as the normal-sighted, and I have examined one dichromic (said to be red-blind by a physicist) who recognised red easily through the thickest neutral glass of my lantern, and who had no difficulty with this colour at a distance.

Apart from any other defect of light or colour-perception, every case with which I have met has fallen naturally into one of the classes I have given; that is to say, every person is either heptachromic, hexachromic, pentachromic, tetrachromic, trichromic, dichromic, or totally colour-blind. When I first gave this classification of colour-blindness, the facts that I discovered were so at variance with those generally stated that it was very difficult for those who were not well acquainted with the subject to compare the two sets. The general knowledge of the subject has, however, steadily increased, and the facts which I had so great a difficulty in getting recognised

now form part of our common knowledge. It would be well, therefore, to describe the two main varieties of colour-blindness which are of chief practical importance, and to show the relation which they bear to the writings of other persons. These two main varieties have dichromic and trichromic vision.

1. *Dichromic vision.*—The cases which come under this head form the class of the ordinary red-green blind. It is under this head that nearly every one of the recorded cases may be classed. Vision, as far as colour is concerned, is dichromic, the neutral point being situated in the green of the normal-sighted at about λ 500. All the colours on the red side tend to be confused with each other; therefore red, orange, yellow and half of the green are seen as one colour, the remainder of the green, blue and violet as the other. The luminosity curve in uncomplicated cases is similar to the normal. There may be shortening of the spectrum at either the red or the violet end of a varying degree. All degrees of shortening of the red end of the spectrum may be found. Dichromics with normal luminosity curves are those which were formerly designated green-blind; but this designation is not in accordance with the facts, because there is no defect of light-perception in the green, and the so-called diagnostic mistakes, as, for instance, putting a bright green with a dark red, are not made. Cases of so-called red-blind are dichromics with shortening of the red end of the spectrum. I have shown that the defective perception of

the red end of the spectrum will not account for the dichromic vision which is found in these cases. We may also meet with shortening of the spectrum with otherwise normal colour-perception. We also meet with dichromic cases forming a series from almost total colour-blindness to those bordering on the trichromic. Any theory must account for the fact that there are varying degrees of colour-blindness in dichromic vision, and why there is a large neutral band corresponding to the colours of the centre of the spectrum in some cases, and in others the neutral band is so small that the dichromic cannot mark it out. The two colours seen by the dichromic are red and violet, though where no distinction is seen between yellow and red, and blue and violet, the brighter colour will often be selected ; that is why so many dichromics say that they see yellow and blue in the spectrum. Those who have had practical experience of colour-blindness will know, however, that many dichromics make no mistakes with the red test. The following will give the normal-sighted the best idea of colour-blindness, and it is how the dichromic see the spectrum, and explains why they are able to distinguish between colours. Let him regard the dichromic as a man who has two colours—red and violet and white. The purest red is at the red end of the spectrum ; this becomes less and less saturated as the violet is approached until the neutral or white point is reached ; then violet comes into the white, and this increases in saturation to the termination of the violet. The ordinary

dichromic therefore sees green as a much whiter and less saturated colour than red.

2. *Trichromic vision.*—These persons see three distinct colours in the spectrum—red, green and violet. They describe the region intermediate between red and green; that is to say, the orange and the yellow as red-green, and blue as violet-green. It will be seen, therefore, that their chief difficulty is distinguishing yellows and blues. A yellow, for instance, which is situated next to a green will be called red, and the same yellow when adjacent to a red will be called green. There are various degrees of trichromic vision, varying from those who are little better than dichromic to those who are tetrachromic. The trichromic rarely find any difficulty with their three main colours—red, green and violet.

These cases have been described under the name of anomalous trichromatics. This name is one which has been given to those persons who in making a match between a yellow corresponding to the sodium flame and a mixture of thallium-green and lithium-red make a mixture which is different to that of the normal.[1] A man who puts too much green in the mixture is called a green anomaly; whilst a man who puts too much red in the mixture is called a red anomaly. The red anomaly is only a trichromic with shortening of the red end of the spectrum, and this may be as extensive as in any case of dichromic vision. I have, however, described trichromic cases which

[1] *Proceedings of the Royal Society*, vol. B 76, 1905.

had all the symptoms attributed to the anomalous trichromatics, but they were not anomalous trichromatics, as they made an absolutely normal match.[1]

[1] *Transactions of the Ophthalmological Society*, 1907, p. 255. *Proceedings of the Royal Society*, vol. B 82, 1910.

LECTURE II

Delivered on February 3rd

The Detection of Colour-Blindness from a Practical Point of View

I. *Object of a test for colour-blindness.*—Tests for colour-blindness are of two kinds; namely, those which are used for the purpose of ascertaining the special phenomena of colour-blindness, and those which are employed when the inquiry is made for some practical purpose. As with visual acuity, it is necessary to fix an arbitrary standard. As we do not wish to exclude a greater number than is absolutely necessary, the object of the test should be to exclude dangerous persons and dangerous persons only. These persons may have other duties to perform which do not require them to possess a perfect colour-sense. I should, however, like to see those persons who are specially qualified for a certain position, occupy it, for instance, men who have to keep a look-out on our most important ships being selected because of their accurate colour-vision and visual acuity. I do not mean that I would select only those men and reject the others, but that I should like to see a second object of a test, namely, to select those who are specially efficient so that the Captain might know on whom to rely in conditions of exceptional difficulty.

II. *The requirements of a test for colour-blindness.*—A test for colour-blindness, when it is to be employed for some definite and specific purpose, as, for instance, excluding dangerous persons from certain callings, should be such as to show definitely that the persons rejected are dangerous. It is very useful to demonstrate to the men and their fellows that a rejected candidate is dangerous. The colleagues of a rejected candidate would refuse to risk their lives with a man who before their eyes called a red light, green. I was expressing these views when a superintendent of a railway company, who is using my lamp, told me that he had adopted this method with great satisfaction to himself and to the men. A man, for instance, who has been working twenty years on the railway has been rejected for colour-blindness. He has complained bitterly to the superintendent, at the same time declaring emphatically that he is normal-sighted. The superintendent has replied, "You know red?"—"Yes." "You know green?"—"Yes." "You will therefore agree that if you call green, red; or red, green, you ought to be rejected. Bring two or three of the other men in with you and I will test you." The man has readily agreed to this. The superintendent has then tested him by asking him to name various coloured objects in the room, and knowing by experience exactly the coloured objects which are miscalled by the colour-blind readily exposes his defect. It is noteworthy that on some occasions a colour-blind man has been tested by another person in the same room with-

out making any of the mistakes which he subsequently made, because none but coloured objects which he could readily recognise were shown to him. This is an example of the necessity of a practical knowledge of colour-blindness in an examiner. On account of the arrangement of signals by sea and land, it is necessary that persons employed in the marine and railway services should be able to recognise and distinguish between the standard red, green, and white lights in all conditions in which they are likely to be placed. An engine-driver or sailor has to name a coloured light when he sees it, not to match it. He has to say to himself, "This is a red light, therefore there is danger"; and this is practically the same as if he made the observation out loud. Therefore, from the very commencement we have colour-names introduced, and it is impossible to exclude them. The engine-driver is told that red is a "danger" signal, green a "caution" signal, and white an "all right" signal. Therefore, it is absolutely necessary that he should know the meaning of these colour-names. A test should be such as to make it impossible for the examinee to be coached through it. This is one of the most important requirements of a test for colour-blindness and one that is rarely fulfilled. Nearly every one of the tests in general use fail on this account.

A test should be one which can be carried out as rapidly as is possible with absolute efficiency; of two equally efficient tests the one which takes the least time must be selected. A test, therefore,

should have no unnecessary details which though of theoretical interest are not concerned with the object in hand. The test should be made as easy and as little complicated for the examiner as possible.

III. *Persons to be excluded.*—We wish to exclude all those individuals who are included in the following three classes: (1) Those who see three or less colours in the spectrum. (2) Those who, whilst being able to perceive a greater number of colours than three, have the red end of the spectrum shortened to a degree incompatible with their recognition of a red light at a distance of two miles. (3) Those who are unable to distinguish between the red, green, and white lights at the normal distance through defect or insensitiveness of the cerebro-retinal apparatus when the image on the retina is diminished in size.

I will now explain why these three classes of persons should be excluded. The first class includes the trichromic, the dichromic, and the totally colour-blind, in accordance with the facts previously stated. The trichromic never, in ordinary circumstances, mistake green for red, but confuse yellow with green or red. Colour is a feeble quality of objects to them, and nervousness or excitement may reduce them to the condition of the dichromic. The dichromic are liable to mistake a green light for red, and vice versa. It is very important that persons belonging to the second class should be excluded, and yet none of the ordinarily used tests detect them. The rays

of red at the extreme left of the spectrum are the most penetrating, as may be seen by looking at a light or the sun on a foggy day, or through several thicknesses of neutral glass. It is chiefly by these rays that we recognise a red light at a distance; and it is therefore of great importance that a sailor or engine-driver should be able to perceive them. The third class contains persons who are able to distinguish colours easily when they are close to, but fail to distinguish them at a distance, owing to the nerve-fibres supplying the central portion of the retina being impaired. As a light at a distance occupies the central portion of the visual field, it is essential that the corresponding portion of the retina should be normal. There are cases of central scotoma for colours with perfect form-vision; these would, therefore, not be detected by a test for visual acuity. This class also includes those who without having a scotoma are unable to distinguish between colours at the normal distance when the image on the retina is diminished in size.

IV. *The construction of a test for colour-blindness.*—In the construction of a test for colour-blindness, the facts of colour-blindness must be utilised so that the object and requirements of the test are fulfilled. The following facts are of practical importance.

1. *Most colour-blind make mistakes with certain colours, but are correct with regard to others.* This may be illustrated in the following way. Let us take an ordinary dichromic, and, having given

him the set of wools belonging to the Classification Test, ask him to pick out all the reds. On examining the pile of wools selected as reds, it will be found that the majority are red, but in addition there will be some browns and yellow-greens. If he be then told to pick out the whole of the greens the greater number of those selected will be green, but there will be also greys, browns, and reds. In each case, it will be seen that the majority of wools are of the desired colour.

If another dichromic be examined in the same way it will be found that, though he may not make exactly the same mistakes, he will in all probability pick out the same greens to put with the reds, and the same reds to put with the greens. The same result will be obtained if the colour-blind persons be asked to name a large number of colours. They will in most cases name the colour correctly. It will be noticed that the greens which were put with the reds when classifying the colours, will be called red in naming them. It is evident that the same idea has guided the colour-blind in each case. This shows that, though a person may be red-green blind, he is not absolutely red-green blind in the sense of being totally unable to distinguish between the two colours. The fact that they are actually judging by colour may be demonstrated by giving them coloured materials of different kinds, or by asking them to name a large number of coloured objects.

It will be seen that if we take a dichromic and ask him to name a number of red and green wools, in the majority of instances he will name them

correctly. But as, almost invariably, the same wools are chosen, for all practical purposes the same result would be obtained by asking a person to name a few of these wools. What more decided and brighter greens could we have than Nos. 76 and 94 of my Pocket Test ? yet these are two of the greens which are called reds by the dichromic. We should have accomplished as much by asking a colour-blind person to name Nos. 76 and 94 as if we had asked him to name a large number of greens. The colours in a test should, therefore, be those which the colour-blind are particularly liable to miscall. At the same time, their nature should be unmistakable to the normal-sighted.

2. *The colour-blind name colours in accordance with their colour-perception, and thus show definitely to which class they belong.* I have not come across a man who has guessed correctly when examined with my test. A man who did guess would know that he was incompetent. As the colour-blind are often not aware of their defect they answer as they see, only guessing when they feel uncertain as to the nature of the colour shown. There is probably more misapprehension on this point than on any other in the practical testing of colour-blindness.

3. *Colours may be changed to the colour-blind, whilst leaving them unaltered to the normal-sighted.*

4. *The phenomena of simultaneous and successive contrast are much more marked for the colour-blind than for the normal-sighted.* Two colours, which have not changed in the slightest degree to the normal-sighted on being contrasted, have appar-

ently altered very considerably to the colour-blind. As an example of this, let us take a pure deep yellow, a bright red, and a bright green. To the normal-sighted the yellow will be altered very little by comparison with the red or the green, but a trichromic would say that the colour was green when contrasted with the red, red when contrasted with the green. This principle of exaggerated contrast must be borne in mind when examining a candidate. Thus if a trichromic be doubtful about a yellow, but seems inclined to call it green, he should be given a pure green to compare with it. In the same way, in showing the coloured lights, the same colour produced in a different way should often be shown. Thus an orange-red may be shown immediately after a pure red. This will not alter the colour to the normal-sighted, but greatly facilitate the examination of the colour-blind.

5. *Many colour-blind match correctly, but name the principal colours wrongly.* Therefore the test must be a naming test, the examinee being rejected if he confuse the colours which it is essential he should distinguish between in his occupation.

6. *Many colour-blind recognise colours easily when they are close to them, or the surface is large, but fail to distinguish between them when they are at a distance or the image on the retina is small.* The test must be constructed in conformity with these facts.

7. *The colour-blind are more dependent upon luminosity than the normal-sighted, and are liable to*

mistake a change in luminosity for a change of colour. The test should have a means of rapidly changing the luminosity of a colour.

8. *The colour-blind find special difficulty with faint and dim colours.* The test should have colours of this kind.

9. *The colour-blind who have shortening of the red end of the spectrum cannot see reds reflecting or transmitting only rays corresponding to the shortened portion.* It is essential that reds of this kind should form part of the test.

10. *The colour-blind find more difficulty in comparing colours when different materials are used, than when the coloured objects are all of the same nature.*

11. *Most colour-blind find more difficulty with transmitted than with reflected light.*

12. *The colour-blind have a defective memory for colours.*

13. *Colours may be changed to the normal-sighted whilst leaving them unchanged to the colour-blind.* When three colours of the normal-sighted are included in one of the colour-blind, it is obvious that a change from one colour to another of the three will make no difference to the colour-blind. Also when the spectrum is shortened, the addition or rays corresponding to the shortened portion to another colour will not alter its appearance to the person with the shortened spectrum. For instance, to a person with shortening of the red end of the spectrum, a blue will still remain blue, when so many red rays from the shortened portion have been added to it as to make it appear rose to the normal-sighted.

14. *The colour-blind may have a sense of luminosity similar to that of the normal-sighted.*

15. *The dichromic distinguish between the colours of the normal-sighted, which are included in one of theirs by their relative luminosity and the difference of saturation which is apparent to them.* A test should therefore have the means of presenting colours of different saturation in succession.

16. *Colour-blindness is frequently associated with very high intelligence and exceptional ability.*

V. *The Lantern Test.*[1]—1. *Description of apparatus.* The lantern contains four discs: three carrying seven coloured glasses, and one with seven modifying glasses. Each disc has a clear aperture. The other mechanical details are: an electric or oil lamp with projecting accessories, a diaphragm for diminishing the size of the light projected, handles for moving the discs and the indicator showing the colour or modifier in use. The diaphragm is graduated in respect to three apertures to represent a $5\frac{1}{2}$-inch railway signal bullseye at 600, 800, and 1000 yards respectively when the test is made at 20 ft. The glasses are as follows:—

Coloured glasses.	*Modifying glasses.*
1. Red (A and B).	7. Ground glass.
2. Yellow.	8. Ribbed glass.
3. Green.	9. Neutral (No. I).
4. Signal Green.	10. ,, (,, II).
5. Blue.	11. ,, (,, III).
6. Purple.	12. ,, (,, IV).
	13. ,, (,, V).

[1] Made by Reiner and Keeler, 9, Vere Street, W.; and Meyrowitz, 1a, Old Bond Street, W.

It will be noticed that three of the discs are similar in every respect. In some of my lanterns the two reds are put at the end of the series of colours and numbered Red 1 and Red 2. This

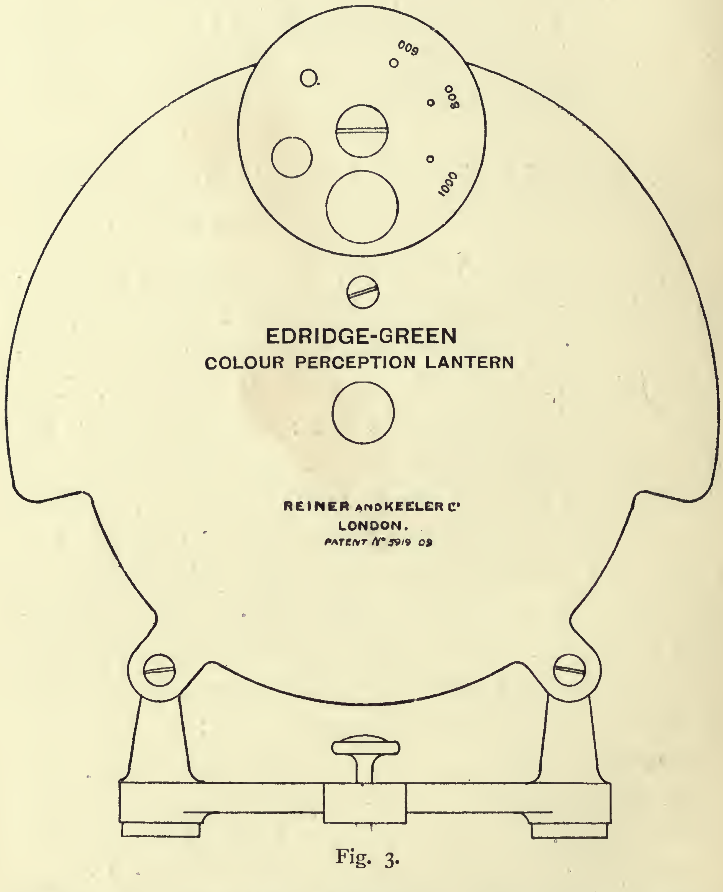


Fig. 3.

makes no important difference, but the arrangement given here is more convenient. It should be noted that Red 1 corresponds to Red B and Red 2 to Red A. If the electric lamp should get broken the projecting apparatus can be

removed and an ordinary kerosene lamp placed behind the aperture.

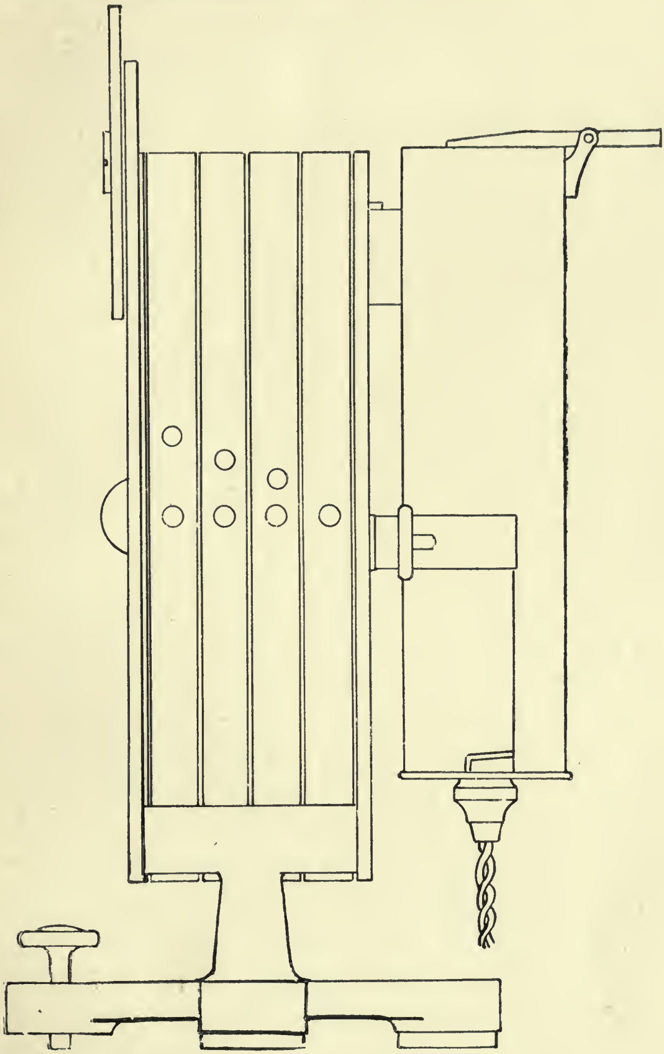


Fig. 4.

2. *Reasons for special construction.*—The lantern has been constructed conformably with the re-

quirements and facts of colour-blindness. All the facts I have given have been considered in constructing the lantern.

The examiner, on possessing a lantern for the first time, should carefully test himself with it and ascertain how the different lights appear to him with different conditions of general illumination. It is probable that certain improvements may suggest themselves to him, therefore, I think it will be advisable to deal with certain of these points, as it will help the examiner in the use of the lantern. The colours have never been altered, and I certainly should have altered them if I could have improved the lantern by doing so. I have never met a single colour-blind person who has not been readily and easily detected with my lantern, though I have examined many who have passed other lanterns and in some cases a number of other tests for colour-blindness. In most cases one turn of the wheel will be sufficient to make a colour-blind person disclose his defect.

The examiner may be dissatisfied with the colour of the blue; let us, therefore, compare an examination of a normal-sighted person with that of an ordinary dichromic. The normal-sighted person will name every one of the colours with ease and certainty, with perhaps the exception of the blue, with which he is in some doubt. Here is the result of an examination of an ordinary dichromic: he called the yellow, green; the green, red; the signal green, no colour; the blue, blue; the purple, green; red A, no colour or light; red B, green. It will be noticed that the only colour

that he has correctly named is the blue. We can try him again and again, and though he will mistake all the other colours he will always name the blue correctly. The examiner will have learnt from this several important facts. He will see that the colour-blind are really guided by their sensations of colour, and that it is not simply a matter of guessing. The more an examiner has practical experience of colour-blindness, the more will he recognise the fact that the colour-blind are guided by their sensations of colour. He will notice that the dichromic has readily recognised the blue which was scarcely apparent to him (the examiner), and therefore cannot have overlooked as a matter of carelessness colours which are much more apparent to the normal-sighted. The blue is a valuable colour for other reasons, for though it is not a colour on which I reject candidates, anyone miscalling it must be very carefully examined before he is passed. The trichromic generally call this blue, green. If we wish to obtain a purer blue, we can do so by combining the blue or the purple with the signal green.

Again, the examiner may think that it might be better to have an apparatus which showed two or three lights instead of only one. I will therefore give my reasons for adopting only one. This point was one which occupied my attention for a considerable time, especially in view of the fact—which, as far as I am aware, I was the first to discover—that simultaneous contrast is increased to the colour-blind. I was naturally anxious to turn this fact to account. I found,

however, that I gained nothing by increasing the number of lights, and that in many cases it was a source of error. A second or third light could have been easily added to my lantern, but besides unnecessarily complicating the apparatus it would have served no useful purpose. All the results which are obtained with simultaneous contrast are obtained even more effectively with successive contrast. It will be noticed that when lights are seen in ordinary conditions they are conditions of successive contrast, and not of simultaneous contrast. An observer rarely keeps his eyes definitely fixed on one light whilst he names those adjacent to it, but moves his eyes so that the images of the respective lights fall successively on his foveas. When more than one light is employed, all the disadvantages of matching as against naming are introduced. It will be seen that by presenting one light after another we are fulfilling all the necessary conditions, only that the light is moved instead of the eyes, sufficient time being allowed to elapse to enable a normal-sighted person to readily recognise the true colour of the next light without being confused by the after-image of the one he has just seen. Many nervous normal-sighted would name a yellow light seen between two red lights as green, and it does look green to them from ordinary physiological conditions. They look first at one red light, then immediately at the yellow light, then at the second red light, and then again at the yellow light until they feel sure that the centre light is a green light, and say so. I have

never met with a normal-sighted person who has miscalled the unmodified light of my lantern, either red or green. Many humble, nervous normal-sighted persons are under the impression that they are colour-blind, and yet would make perfectly efficient officers. Many of these men have been told by their wives or other persons that they are colour-blind, and, believing this, try to see colours which are not visible to them. I have examined many persons of this description, and have noted the ease and accuracy with which they have gone through the tests for colour-blindness when they have been assured by me that they were normal-sighted. On the other hand, it is often very difficult to convince a self-reliant, colour-blind person that he is colour-blind. He is on the look-out for the small differences which he notices between colours, and the fact of having another light for comparison gives him the desired clue, and, though colour-blind, he passes the test.

The material is the best possible, as it will not fade like all dyed substances, and therefore all records made with one set of apparatus will be uniform. Again, a coloured light has none of the accessory qualities which enable the colour-blind to pass through other tests. Thus many dichromics will call the yellow glass red or green, who would not think of putting a yellow with a green or red wool, on account of the difference in luminosity. He will, in the same way, if told to pick out colours in the Classification Test to match the colour of the light shown, have to depend upon his colour-perception. This is a

useful method with nervous and undecided candidates. The objection to it is that it cannot be carried out in the dark or in a dark room. The Test is not open to any of the objections which may be urged against the method of simply naming colours, because the character and intensity of the colour may be changed at will.

The method is better than that of direct comparison, because the candidate is forced to use his colour-perception, and has to compare the colour seen with previous impressions of colour in his mind. By the use of neutral glasses, etc., I have obviated the fallacy of the method of naming colours (namely, that these can be distinguished by their saturation and luminosity), and forced the individual to depend upon his colour-perception, and not upon some other accessory quality of the object seen.

No amount of coaching will enable a colour-blind person to pass this test, whilst almost any other may be passed in this way. I have tried on many occasions to coach a man so as to pass my lantern, and without success. The combinations are so numerous that the only result is to make the colour-blind man nervous and doubtful and more easily detected than before. This has occurred with men who could pass other tests with ease.

The test also has a quality possessed by no other—namely, that of enabling the examiner to reject dangerous persons and dangerous persons only, the lower degrees of colour-blindness being allowed to pass.

3. *Special directions for conducting the test.*—(1) The candidate should be seated at a distance of twenty feet from the lantern. (2) He should be asked to name the colour of the light produced by a coloured glass (1 to 6) alone, or in combination with another coloured glass or glasses, or with the modifying glasses (7 to 13). (3) A candidate should be rejected (i) if he call the red, green, or the green, red, in any circumstances; (ii) if he call the white light, in any circumstances, red or green, or vice versa; (iii) if he call the red, green, or white lights, black, in any circumstances. (4) A candidate who makes mistakes, other than those mentioned above, should be put through a very searching examination. It is not necessary to have the room absolutely dark; in fact, I prefer a certain amount of light. The examiner can, if he wish, make the test at night in the open air.

The examiner should on no account conduct the examination on any regular plan, because the candidate, anxious to pass, finds out from persons who have already passed the order and method of the examination, and so, though colour-blind, might obtain a certificate. Any one of the glasses may be shown first, and the candidate required to name the colour of the light. The following will serve as an example of the method to be employed in testing a candidate. A red being shown, the candidate is required to name its colour. Then a blue or green may be substituted. It is best to use the largest aperture at first and to show all the colours on one disc. This will

give confidence to the normal-sighted candidate, whilst most of the colour-blind will be detected. In the case of candidates who appear to be normal-sighted and yet very nervous, there is no harm in telling them after they have named all the colours on the disc correctly that this is the case. No comment should, however, be made on individual answers. Then one of the neutral, ground, or ribbed glasses should be inserted, not the slightest intimation being given to the candidate of the nature of the colour. He should be asked to name or describe the light, and the answer, if incorrect, together with his other replies, carefully recorded. The other glasses may then be shown, a combination of the neutral, ground, ribbed, and coloured glasses being used at irregular intervals.

When the candidate has been examined with the largest aperture, the examiner can go through the same procedure with one of the smaller apertures. I have found the third aperture the one which is most generally useful. On account of the great diminution of total luminosity caused by the diminished area of the light source, the three smallest apertures can only be used in a dark room.

If a candidate hesitate about a colour and ultimately name it correctly, a second and, if necessary, a third glass of the same colour should be combined with the first. The fact that in one case a single glass is used, and in another two or three of the same coloured glass, makes very little difference in the colour of the light to the normal-

sighted. This is not the case with the colour-blind; a dichromic who has hesitated about a green and then correctly named it may emphatically call the light red when another green glass is put in front of the first.

Care must be taken when the candidate is going to be examined with two glasses at once, such as one of the neutral, ground, or ribbed glasses, and a coloured glass, that he does not see the light until both are in position, or else he may see the colour before it is modified in the necessary way.

If the candidate call the standard red, green; or the standard green, red, in any circumstances—that is, either alone or in combination with the modifying glasses—he is to be rejected.

The examiner should ascertain for himself how far the various colours are visible when modified with the neutral glasses. If the red and green be not visible with the thickest neutral in the conditions of luminosity and external lighting which the examiner is employing, he should use the darkest neutral which allows the colours to be plainly visible to the normal-sighted. In all cases of doubt the examinee should be asked to walk towards the lantern and told to say when the light is visible, and asked to name its colour. The distance at which the light is visible, and then that at which the colour is visible, should be noted and compared with the normal.

Particular attention should be paid to the answers given to the combination of the thickest neutral glass with the standard red and green respectively.

The examiner should utilise the fact that successive contrast is increased in the colour-blind, as this is an easy method of detecting the trichromics. The red having been shown, the light should be quickly changed to yellow or clear, the examiner's hand being placed over the aperture if there be any intervening colours. It is necessary that the yellow should be shown immediately after the red without any intervening colours being first seen by the candidate. The normal-sighted do not see any change in the yellow or clear when they are shown after the red light, but the trichromic call the yellow light, green. The examinee should then be shown the green light, and then the yellow or clear, in the same way as mentioned for the red. The normal-sighted will easily recognise the yellow, but the trichromic will call it red. This portion of the examination must never be omitted in any examination in which the candidate is passed. The two divisions of the test—that is, showing yellow immediately after red and after green—may be used at different periods of the examination, and, if there be any doubt, repeated.

An examiner should, as far as possible, with the exceptions given in the instructions, avoid all conversation with the candidate, simply asking, "What colour is this?" and recording the answer without comment. If an examiner after each answer say, "Quite right," or some such expression, the following is likely to occur. The candidate after, say, six correct answers, makes a mistake; the examiner says, "Are you sure?"

Then the candidate knows at once that he has made a mistake, and makes a guess, very probably a correct one. When a similar colour is shown subsequently, he remembers the mistake he made, and gives the second, and probably the correct answer.

In addition to being an efficient test, it is a very rapid test, as many men who have been certified as normal after a lengthy examination with other tests have at once disclosed their defect by calling the green light of the lantern red. Many are under the impression that in an examination with the lantern the dichromics simply guess. This is entirely wrong. A man who did guess would know that he was incompetent. I find that men have named the coloured lights in strict accordance with their colour-perception. A man may, however, guess if examined by an inexperienced and ignorant examiner, who when the examinee has made a mistake promptly corrects it in a cross tone. A normal-sighted person will guess when examined in this way. The examiner must receive the examinee with a smiling face and courteous manner, and appear pleased and satisfied with the answers, no matter what they may be. The candidate is then placed at his ease, and answers according to his colour-perception. It will be noticed that the lantern detects those who have a slightly diminished colour-perception, as well as the dangerous varieties of colour-blindness. The former undoubtedly are not as efficient as those who have a normal colour-perception, so that a definite standard will have to be fixed, as

in the case of visual acuity. Further details will be found in my book on Colour-Blindness.[1]

Summary of method of examination.—(1) Show all the colours on one disc with the largest aperture. (2) Show the reds, greens, and yellow modified by the neutral glasses. (3) Show all the colours on one disc with Number 3 aperture. (4) Show red, then immediately afterwards yellow with largest aperture. Then show green and yellow immediately afterwards. (5) Test the candidate with the red, green, and yellow with the smallest aperture. (6) Show the neutrals or ground glass alone. (7) Show blue made by combining blue or purple with the signal green. (8) Show a colour, for instance, green, and then combine another glass of the same colour. (9) Show the red produced by the combination of purple with red A. (10) Give the combination of red A and signal green.

VI. *Other tests for colour-blindness.*—I have three other tests for colour-blindness: the Classification Test, the Pocket Test, and the Colour-perception Spectrometer. I have also devised an instrument for estimating the exact amount of red, at different wave-lengths, which is necessary to neutralise the complementary in different persons.

1. *The Classification Test.*—(*a*) *Description.*—This test consists of 4 test colours and 180 confusion colours; 150 coloured wools, 10 skeins of silk, 10 small squares of coloured cardboard, and 10

[1] *International Scientific Series.* Kegan Paul & Co., 1909.

small squares of coloured glass. The whole series of colours is represented. In addition, there are a large number of colours which have been chosen by colour-blind persons as matching the test colours. The test colours are Orange, Violet, Red, and Blue-green, labelled I, II, III, and IV respectively. The colours are chosen with the view of presenting as much difficulty as possible to the colour-blind, and as little as possible to the normal-sighted. The colour-blind find especial difficulty in matching or naming a colour lying at the junction of two of their colours. As the normal-sighted often find difficulty in saying which colour predominates in a blue-green, so do the tetrachromic with their purple-green, or the trichromic with their red-green. A colour-blind person may, however, match a colour correctly which corresponds to the centre of one of his colours. In addition to choosing those colours for tests which are particularly liable to be mistaken for other colours by the colour-blind, I have used coloured materials of different kinds—wools, silks, glass, and cards—so as to force the colour-blind to judge by colour, and not by saturation or luminosity. (See Fig. 5.)

(*b*) *Method of examination.*—The candidate should be given the four test colours, and, having named each, he should be told to select all those which are similar in colour to the test colour. He should be told to pay no attention to the fact of a colour being lighter or darker; as long as it is the same colour it should be put with the test skein. The examiner should not go through the

test before the candidate first of all, neither should one candidate be allowed to watch another making his selection. A shrewd colour-blind person might pass the test if he had seen a normal-sighted person go through it previously. In order to show the candidate the difference between a shade and a colour, the examiner should take

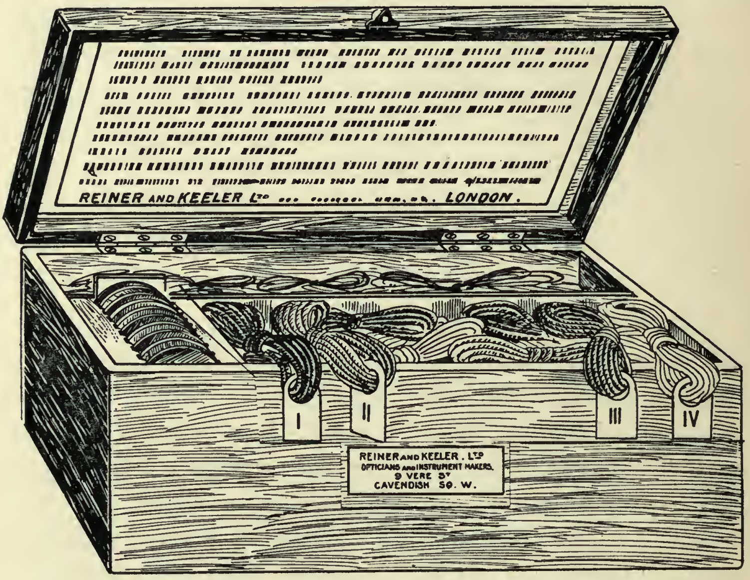


Fig. 5.

one of the wools which is not a test colour—blue, for instance—and pick out four or five shades of the colour. The wools should be arranged without the knowledge of the candidate, so that a yellow or a grey is placed beside a red and the examinee asked to name its colour. At another period of the examination the yellow should be placed adjacent to a green, and the examinee again asked to name it.

The examinee may pick out a certain number of colours correctly, and then stop, saying that there are no more exactly like the test colour. This may embarrass the examiner; he should, however, examine any candidate who has omitted any colours as carefully as if mistakes had been made. He should ask the candidate to match one of the omitted colours.

The examiner will soon find out from experience those colours which are named and matched wrongly by colour-blind persons; he should ask the examinee to name some of these colours.

Any candidate should be rejected who calls an orange or red, green or brown; black, red or vice versa; or green, either purple, rose, red, grey, brown, or violet. Similar mistakes in matching necessitate objection. A candidate who puts purple, rose, or blue with violet, or yellow-brown with orange is most probably dangerously colour-blind and should be very carefully examined. There are cases which pass the Holmgren test with ease that fail in the most conclusive manner with my Classification Test. They put green with orange, brown and black with red, and grey with blue-green. This is due to a different selection both of test colours and confusion colours. Orange is by far the most important test colour, and its confusion with green by the dichromics is very conclusive. The three other test colours, violet, red, and blue-green, represent both ends of the spectrum and the neutral point in dichromic cases, and practically these colours are those with which most mistakes are made. This test can only be regarded as supplementary to the Lantern Test.

2. *The Pocket Test.*—This consists of nineteen cards, on nine of which are 112 single threads of wool, and 14 pieces of twisted silk, similar to those in the Classification Test. These are numbered consecutively, with the exception of the first thread of the first four cards, and the last thread of the next four cards. The end threads of the first

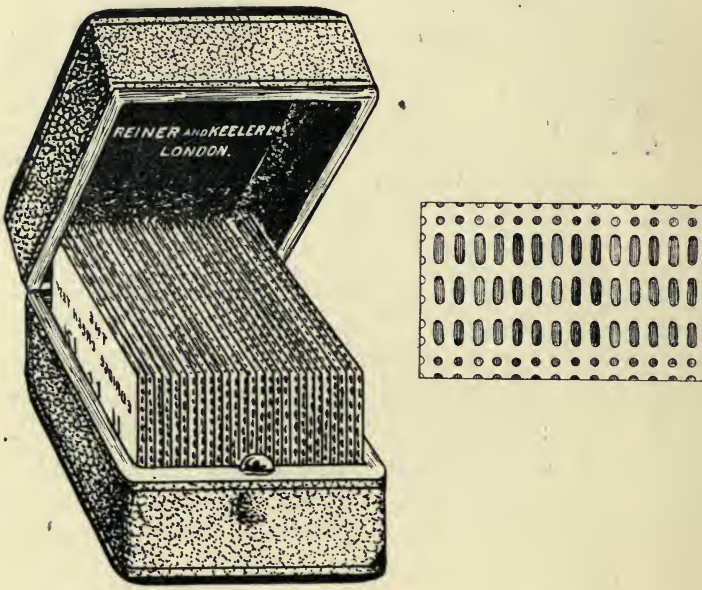


Fig. 6.

four cards, I to IV, form the tests; they are Orange, Violet, Red, and Blue-green. There are also cards on which red, orange, green, blue, violet and purple, and grey, respectively are to be found. There are also two special cards marked "Without Red" and two special cards marked "Without Green." (See Fig. 6.)

Many normal-sighted persons might object to the

inclusion of some of the colours on the orange card, but this card clearly shows the colours which may be taken as a match. Fine distinctions are not wanted. The series of colours I have selected and arranged so as to confuse the colour-blind and force them to be guided by their colour-perception, whilst the quantity of colour is amply sufficient for the normal-sighted to pick out the colours with the greatest ease. The cards should be arranged irregularly on a white cloth in a good light. The two most important tests colours are the Orange and Violet, Nos. I and II. The person examined should be asked to point out the shades of colour similar to No. I (Orange). A piece of paper rolled to a point should be used for this purpose. If he do this correctly, he probably possesses normal colour-perception. If, however, he match the test with reds or pinks, he is more or less colour-blind, at best belonging to the pentachromic class. If, in addition, he match the Violet test, No. II, with blue, he at least belongs to the tetrachromic class. The trichromic, in addition, may match the Blue-green test, No. III, with brown and grey. The dichromic will match the Orange test, No. I, with yellow-green and yellow-brown. Similar mistakes will be made to those described in connection with the Classification Test. The examinee should be asked to name all the colours on one of the cards. He should also be asked to point out on which of the cards the four tests colours are to be found, and which contain none of the test colour.

The examiner should continually change the

order of the cards. Most of the varieties of the colour-blind will be readily detected in this way.

The special advantages of this test are: (1) The colour-blind can be ranged definitely in their proper classes. (2) Central scotoma can be detected with its aid. (3) The series of colours are arranged so as to confuse the colour-blind, whilst the normal-sighted easily match the test colours. (4) On account of the introduction of different materials, the relative luminosity and saturation of colours does not serve as a guide to the colour-blind. (5) Portability. (6) The wools and silks are kept clean. (7) An important colour is not likely to be lost.

3. *The Colour-Perception Spectrometer.*[1]—(*a*) *Description of apparatus.*—This instrument is a spectrometer so arranged as to make it possible to expose to view in the eyepiece the portion of a spectrum between any two desired wave-lengths. In the focal plane of the telescope are two adjustable shutters with vertical edges; the shutters can be moved into the field from right and left respectively, each by its own micrometer screw, and to each screw is attached a drum, the one being on the right and the other on the left of the telescope. On each of these drums is cut a helical slot in which runs an index, and the drum is engraved in such a manner that the reading of the index gives the position in the spectrum of the corresponding shutter in wave-lengths direct. (See Fig. 9.) Thus it will be seen that if, for instance, the reading on

[1] Made by A. Hilger, 75a, Camden Road, London, N.W.

the left drum-head is 5320 and that on the right drum-head is 5920, the region of the spectrum from

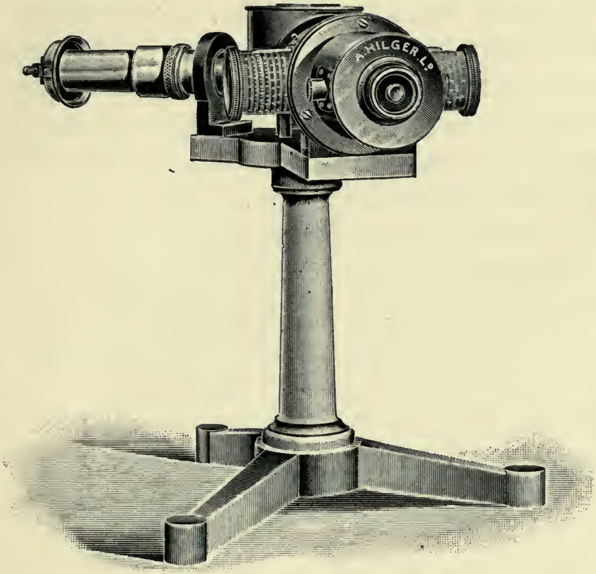
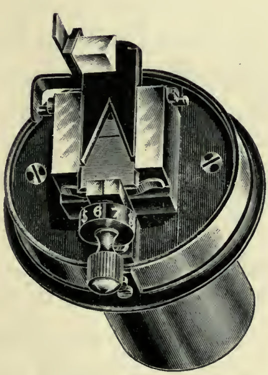


Fig. 7.



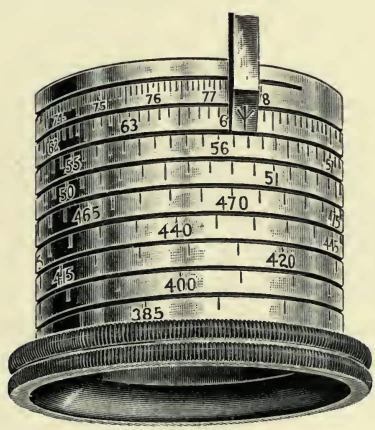


Fig. 8.

Fig. 9.

wave-length 5320 to wave-length 5920 is exposed to view in the eyepiece.

(*b*) *Directions for using the instrument.*—It should be used as far as possible with a known quality and intensity of light. A small oil-lamp is quite suitable for the purpose. The observer should first ascertain the exact position of the termination of the red end of the spectrum, the left-hand shutter being moved across until every trace of red just disappears. The position of the pointer on the left-hand drum is noted, and the wave-length recorded. The left drum is then moved so that the shutter is more towards the middle of the spectrum. The right-hand drum is then moved, until the pointer indicates the wave-length recorded as the termination of the red end of the spectrum. The observer then moves the left-hand shutter in and out until he obtains the largest portion of red, which appears absolutely monochromatic to him, no notice being taken of variations in brightness, but only in hue. The position of the index on the left-hand drum is recorded. The left-hand shutter is then moved towards the violet end of the spectrum, the right-hand shutter being placed at the position previously occupied by the left-hand shutter. In this way the whole of the spectrum is traversed until the termination of the violet end of the spectrum is finally ascertained with the right-hand shutter. The variation of the size of the patches and the terminations of the spectrum with different intensities of light can be noted. The instrument can also be used for ascertaining the exact position and size of the neutral patch in dichromics, the position of greatest luminosity, and the size and

extent of pure colours. When it is used to test colour-blindness, the examinee should first be shown some portion of the interior of the spectrum, and then asked to name the various colours which he sees. In this way he will have no clue to the colours which are being shown him.

Objections to other tests for colour-blindness.—The tests which have been proposed for colour-blindness are very numerous, but some are so defective that it is rare to detect a single colour-blind person with them. I have, for instance, tested men whom I knew to be colour-blind with certain lanterns with the result that not a single one was detected. In these so-called tests all the requirements of a test and facts of colour-blindness have been neglected. I must, however, refer to three tests constructed by exceptionally able men, each with considerable knowledge of the subject. I refer to the tests of Professor Holmgren, Professor Stilling, and Professor Nagel.

All these tests can be passed at the first attempt without coaching by certain dangerously colour-blind persons, chiefly varieties not known to the inventors, but the chief defect of each is that it is very easy to coach a colour-blind person to pass it. The surgeon to one of our largest railway companies told me that when they used Holmgren's test they rejected one man in three hundred, but with my lantern twelve in the same number. All these three tests are much better tests when the persons to be examined have not seen them before. A colour-blind man may make only one mistake, say for instance, as in a case I examined the other

day, with Nagel's test (last edition), he passes the test perfectly with the exception of one mistake, that of calling a grey on one card, green. All he has to do is to look for some distinguishing mark on this card in order to go through the test with the ease and certainty of a normal-sighted person. It is the same with Stilling's letters, he has only to note the letter which he was not able to read and the appearance of the card. A normal-sighted man or woman would readily help him. The confusion of green and grey does not appeal to the average man as a serious defect, especially when he sees his friend go through the rest of the test perfectly. He says to himself, "I suppose he sees a tinge of green in that grey." The same man would rightly regard it as a most iniquitous proceeding to endeavour to coach his friend through a test when he had seen him mistake a red for a green light.

Holmgren's test rejects a large number of normal-sighted persons, as may be seen by the reports of the Board of Trade; about 50 per cent of those who appeal are found to be normal-sighted and to have been rejected wrongly.

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